

We Claim:

1. A method of processing signals to be transmitted to receivers on a plurality of communication channels, comprising:

5 determining pre-coding signal weights based on channel state information associated with the plurality of communication channels to provide proportional power allocation to the signals; and

applying the signal weights to the signals.

10 2. The method of claim 1, further comprising receiving the channel state information from the receivers.

3. The method of claim 1, wherein the signal weights are elements of a pre-coding matrix  $P$ , and wherein determining  
15 further comprises determining the signal weights to enhance diagonal elements of a combined communication channel matrix  $C=HP$ , where  $H$  is a matrix of the channel state information.

4. The method of claim 3, wherein determining the signal  
20 weights to enhance diagonal elements comprises determining the signal weights to maximize the diagonal elements of  $C$ , and wherein determining pre-coding signal weights further comprises determining the signal weights to force off-diagonal elements of  $C$  to zero.

5. The method of claim 4, wherein  $P = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix}$ , wherein

$H = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$ , and wherein determining comprises selecting the signal weights of  $P$  such that

$$|p_{11}| \propto \left| h_{11} - \frac{h_{12}h_{21}}{h_{22}} \right|;$$

5  $|p_{22}| \propto \left| h_{22} - \frac{h_{12}h_{21}}{h_{11}} \right|;$

$$p_{12} = -\frac{h_{12}p_{22}}{h_{11}}; \text{ and}$$

$$p_{21} = -\frac{h_{21}p_{11}}{h_{22}}.$$

6. The method of claim 3, implemented in a transmitter  
 10 having  $M$  antennas comprising sub-groups of antennas  
 respectively associated with sub-groups of the plurality of  
 communication channels, wherein  $C$  comprises a plurality of  
 groups of rows respectively associated with the sub-groups of  
 the plurality of communication channels and a plurality of  
 15 groups of columns respectively associated with the sub-groups  
 of the antennas, and wherein determining pre-coding signal  
 weights further comprises determining the signal weights to  
 force each element of  $C$  positioned in a row associated with one  
 of the sub-groups of the plurality of communication channels  
 20 and a column associated with a sub-group of antennas that is  
 associated with a different one of the sub-groups of the  
 plurality of communication channels to zero.

7. The method of claim 6, wherein the sub-groups of the plurality of communication channels comprise  $U$  sub-groups each having  $N$  communication channels, wherein  $M=U*N$ , wherein the sub-groups of antennas comprise  $M/U$  sub-groups each having  $N$  antennas, wherein each of the plurality of groups of rows comprises  $N$  rows, and wherein each of the plurality of groups of columns comprises  $N$  columns.

8. The method of claim 6, wherein the sub-groups of the plurality of communication channels comprise  $U$  sub-groups, an  $i$ th sub-group of the plurality of communication channels having  $N_i$  communication channels, wherein  $M=\sum_{i=1}^U N_i$ , wherein the sub-groups of antennas comprise  $M/U$  sub-groups, wherein an  $i$ th sub-group of the antennas comprises  $N_i$  antennas, wherein an  $i$ th group of rows of the plurality of groups of rows comprises  $N_i$  rows, and wherein an  $i$ th group of columns of the plurality of groups of columns comprises  $N_i$  columns.

9. The method of claim 7, wherein  $M=4$ ,  $N=2$ ,  $U=2$ , and wherein determining comprises selecting the signal weights of  $P$  such that

$$C = HP = \begin{bmatrix} c_{11} & c_{12} & 0 & 0 \\ c_{21} & c_{22} & 0 & 0 \\ 0 & 0 & c_{33} & c_{34} \\ 0 & 0 & c_{43} & c_{44} \end{bmatrix},$$

where the group of the first two rows of  $C$  is associated with a first of the two sub-groups of the plurality of communication channels, the group of the third and fourth rows of  $C$  is

associated with a second of the two sub-groups of the plurality of communication channels, the group of the first two columns of  $C$  is associated with a first of the two sub-groups of two antennas, and the group of the third and fourth columns of  $C$  is  
5 associated with a second of the two sub-groups of two antennas.

10. The method of claim 1, wherein applying comprises a first interference cancellation operation of an interference cancellation task, and wherein the interference cancellation  
10 task further comprises a second interference cancellation task to be performed at the receivers.

11. The method of claim 10, wherein the signals comprise respective groups of signals to be transmitted to the  
15 receivers, wherein determining further comprises determining the pre-coding signal weights to separate the respective groups of signals.

12. The method of claim 11, implemented at a transmitter  
20 in a multi-user MIMO (Multiple Input Multiple Output) communication system that provides respective  $N \times N$  sub-MIMO channels from the transmitter to the receivers, wherein each of the groups of signals comprises  $N$  signals.

25 13. The method of claim 12, wherein determining comprises determining elements of a pre-coding matrix  $P$  such that a combined communication channel matrix  $C = HP$  has a form of  $U$   $N \times N$  sub-matrices, diagonal elements of which are respective

diagonal elements of  $C$ , and elements of  $C$  outside the plurality of  $N \times N$  sub-matrices are forced to zero.

14. The method of claim 13, wherein the transmitter has  $M=4$

5 antennas, wherein  $U=2$ ,  $N=2$ ,  $P = \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \\ p_{41} & p_{42} & p_{43} & p_{44} \end{bmatrix}$ ,

$$H = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix}, \quad C = HP = \begin{bmatrix} c_{11} & c_{12} & 0 & 0 \\ c_{21} & c_{22} & 0 & 0 \\ 0 & 0 & c_{33} & c_{34} \\ 0 & 0 & c_{43} & c_{44} \end{bmatrix}, \text{ wherein determining}$$

elements of  $P$  comprises:

selecting  $p_{31}$ ,  $p_{41}$ ,  $p_{32}$ , and  $p_{42}$  to force

$$c_{13} = c_{14} = c_{23} = c_{24} = 0;$$

$$10 \quad \text{selecting} \begin{cases} p_{11} = \nu a_{11}^* \\ p_{21} = \nu a_{12}^* \\ p_{12} = \nu a_{21}^* \\ p_{22} = \nu a_{22}^* \end{cases}, \text{ where } \nu \text{ is a power normalization}$$

factor and  $a_{ij}$  are elements of  $A$ , where

$$A = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} - \frac{1}{\Delta} \begin{bmatrix} h_{13} & h_{14} \\ h_{23} & h_{24} \end{bmatrix} \begin{bmatrix} h_{44} & -h_{34} \\ -h_{43} & h_{33} \end{bmatrix} \begin{bmatrix} h_{31} & h_{32} \\ h_{41} & h_{42} \end{bmatrix} \text{ and } \Delta = h_{33}h_{44} - h_{34}h_{43};$$

selecting  $p_{13}$ ,  $p_{23}$ ,  $p_{14}$ , and  $p_{24}$  to force

$$c_{31} = c_{32} = c_{41} = c_{42} = 0; \text{ and}$$

$$\text{selecting } \begin{cases} p_{33} = va_{11}^* \\ p_{43} = va_{12}^* \\ p_{34} = va_{21}^* \\ p_{44} = va_{22}^* \end{cases}, \text{ where } a_{ij} \text{ are elements of } A,$$

where

$$A = \begin{bmatrix} h_{33} & h_{34} \\ h_{43} & h_{44} \end{bmatrix} - \frac{1}{\Delta} \begin{bmatrix} h_{31} & h_{32} \\ h_{41} & h_{42} \end{bmatrix} \begin{bmatrix} h_{22} & -h_{12} \\ -h_{21} & h_{11} \end{bmatrix} \begin{bmatrix} h_{13} & h_{14} \\ h_{14} & h_{24} \end{bmatrix}, \text{ and } \Delta = h_{11}h_{22} - h_{12}h_{21}.$$

5 15. A computer program product comprising a computer-readable medium storing instructions which, when executed by a processor, perform the method of claim 1.

16. The method of claim 1, further comprising:

10 transmitting the weighted signals to the receivers on the plurality of communication channels; and

at each of the receivers:

15 receiving a subset of the weighted signals over a sub-group of the plurality of communication channels; and

20 decoding the received subset of the weighted signals using inverses of the pre-coding signal weights based on channel state information associated with the sub-group of the plurality of communication channels.

17. A method comprising:

receiving over a sub-group of a plurality of communication channels a subset of a plurality of signals to which pre-coding signal weights based on channel state information associated with the plurality of communication  
5 channels to provide proportional power allocation have been applied; and

decoding the received subset of the plurality of signals using inverses of the pre-coding signal weights based on channel state information associated with the sub-group of  
10 the plurality of communication channels.

18. The method of claim 17, further comprising:

determining the channel state information for the sub-group of the plurality of communication channels.

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19. The method of claim 18, wherein receiving comprises receiving the subset of the plurality of signals from a transmitter, further comprising:

transmitting the channel state information for the  
20 sub-group of the plurality of communication channels to the transmitter.

20. The method of claim 17, wherein the pre-coding signal weights are elements of a pre-coding matrix  $P$  determined to  
25 enhance diagonal elements of a combined communication channel matrix  $C=HP$ , where  $H$  is a matrix of the channel state information associated with the plurality of communication channels, and wherein decoding comprises decoding the received

subset of the plurality of signals using an inverse of either  $P$  or  $C$ .

21. The method of claim 20, wherein the inverse is a  
5 Moore-Penrose pseudo-inverse matrix.

22. The method of claim 17, wherein receiving comprises  
receiving the subset of the plurality of signals at respective  
antennas.

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23. The method of claim 17, wherein the pre-coding  
weights separate the plurality of signals into subsets  
comprising the subset of the plurality of signals as a first  
interference cancellation operation, and wherein decoding  
15 comprises performing a further interference cancellation  
operation.

24. The method of claim 23, wherein decoding comprises ML  
(Maximum Likelihood) decoding.

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25. The method of claim 23, wherein performing a further  
interference cancellation operation comprises separating  
individual signals from the subset of the plurality of signals.

25 26. The method of claim 17, implemented at a receiver in  
a multi-user MIMO (Multiple Input Multiple Output)  
communication system that provides an  $N \times N$  sub-MIMO channel to



the receiver, wherein the subset of the plurality of signals comprises  $N$  signals.

27.           The method of claim 26, wherein the pre-coding signal  
5 weights are elements of a pre-coding matrix  $P$  determined such that a combined communication channel matrix  $C=HP$  has a form of  $U$   $N \times N$  sub-matrices, and wherein decoding comprises decoding the received subset of the plurality of signals using an inverse of one of the  $U$   $N \times N$  sub-matrices.

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28.           A computer program product comprising a computer-readable medium storing instructions which, when executed by a processor, perform the method of claim 17.

15 29.           A system for processing signals to be transmitted to receivers on a plurality of communication channels comprising:

an input for receiving the signals; and

a processor configured to determine pre-coding signal  
weights based on channel state information associated with the  
20 plurality of communication channels to provide proportional power allocation to the signals, and to apply the signal weights to the signals.

30.           The system of claim 29, wherein the processor is  
25 further configured to determine the pre-coding signal weights to cancel interference between groups of the signals.

31. The system of claim 29, implemented in a multi-user MIMO (Multiple Input Multiple Output) communication system, further comprising:

a plurality of antennas,

5 wherein the plurality of antennas provides respective sub-MIMO channels to the receivers.

32. The system of claim 29, implemented at a network element of a communication network, the communication network  
10 further comprising a plurality of receivers, each of the plurality of receivers comprising:

an input for receiving a subset of the weighted signals over a sub-group of the plurality of communication channels; and

15 a processor configured to decode the received subset of the weighted signals using inverses of the pre-coding signal weights based on channel state information associated with the sub-group of the plurality of communication channels.

20 33. The system of claim 32, wherein the communication network is selected from the group consisting of: a MIMO system is a MIMO BLAST system.

34. The system of claim 32, wherein the processor of each  
25 of the plurality of receivers is further configured to determine and feed back to the network element a portion of the channel state information.

35. A system comprising:

an input for receiving over a sub-group of a plurality of communication channels a subset of a plurality of signals to which pre-coding signal weights based on channel state information associated with the plurality of communication channels to provide proportional power allocation have been applied; and

a processor configured to decode the received subset of the plurality of signals using inverses of the pre-coding signal weights based on channel state information associated with the sub-group of the plurality of communication channels.

36. The system of claim 35, wherein the processor implements an ML (Maximum Likelihood) decoder.

37. The system of claim 35, wherein the processor is further configured to cancel interference between each signal in the subset of the plurality of signals.

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38. The system of claim 35, implemented in a MIMO (Multiple Input Multiple Output) communication system, further comprising:

a plurality of antennas,

25 wherein the plurality of antennas provides a sub-MIMO communication channel comprising the sub-group of the plurality of communication channels.

39. A method of processing signals to be concurrently transmitted to receivers over a plurality of communication channels comprising:

5 determining channel state information for the plurality of communication channels;

determining a spatial coding matrix comprising a respective set of spatial coding weights for each of the receivers based on the channel state information; and

10 applying the spatial coding weights in the spatial coding matrix to the signals.

40. The method of claim 39, wherein the signals comprise a plurality of groups of at least one signal to be transmitted  
15 to respective ones of the receivers.

41. The method of claim 40, wherein the plurality of groups of signals comprises groups of signals comprising different numbers of signals.

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42. The method of claim 39, wherein determining channel state information comprises:

receiving portions of the channel state information from the receivers; and

25 combining the portions of the channel state information to form the channel state information.

43. The method of claim 40, further comprising:

transmitting the signals to the receivers,

wherein the spatial coding matrix  $F$  comprises

5 elements  $[F^{(1)}, F^{(2)}, \dots, F^{(U)}]$ ,  $U$  an integer, where each element  $F^{(i)}$  is the set of spatial coding weights for an  $i^{th}$  one of the receivers and satisfies  $tr\{F^{(i)}F^{(i)'}\} = tr\{F^{(i)'}F^{(i)}\} = P_s$ ,  $i=1, 2, \dots, U$ , where  $tr\{\bullet\}$  is the trace of a matrix, and  $P_s$  is a total transmitted power of the signals.

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44. The method of claim 43, implemented in a MIMO (Multiple Input Multiple Output) communication system, wherein determining a spatial coding matrix comprises determining the elements  $F^{(i)}$  of  $F$  as

$$15 \quad F^{(i)} = \sqrt{P_s} \frac{\hat{G}^{(i)'}}{\sqrt{tr(\hat{G}^{(i)} \hat{G}^{(i)'})}},$$

where

$\hat{G}^{(i)} = \hat{H}_F^{(i)'} (\hat{H}_F \hat{H}_F' + I_{N_i})^{-1}$ ,  $i=1, 2, \dots, U$ , is a set of the demodulation weights corresponding to  $F^{(i)}$ ;

$$\hat{H}_F = [\hat{H}_F^{(1)}, \dots, \hat{H}_F^{(U)}];$$

20  $\hat{H}_F^{(i)} = (\hat{H}^{(i)} \hat{F}^{(i)}) / \sqrt{2\sigma_{\eta,i}^2}$  is a combined channel matrix of a virtual reverse MIMO channel from the  $i$ th receiver;

$\hat{H}^{(i)} = [H^{(i)}]^T$  is a matrix of channel state information of the virtual reverse MIMO channel from the  $i$ th receiver;

$H^{(i)}$  is a matrix of channel state information for a forward MIMO channel of the plurality of channels to the  $i$ th receiver;

5  $\hat{F}^{(i)}$  is a space coding matrix of the virtual reverse MIMO channel from the  $i$ th receiver;

$I_{N_i}$  is a unit matrix;

$N_i$  is a number of signals in the one of the plurality of groups of signals to be transmitted to the  $i$ th receiver; and

10  $\sigma_{n,i}^2$  is a variance of a component of noise at the  $i$ th receiver.

45. The method of claim 44, further comprising:

transmitting a respective set of demodulation weights  
15  $\hat{G}^{(i)}$  to each of the receivers.

46. The method of claim 44, wherein  $\hat{F}^{(i)} = \bar{V}^{(i)} \Phi^{(i)}$

where

$\bar{V}^{(i)}$  is a matrix constructed from columns of  $V^{(i)}$ ;

20  $V^{(i)}$  is a unitary matrix resulting from the singular decomposition of a channel matrix  $H^{(i)}$  of a MIMO channel to the

ith receiver as  $\tilde{H}^{(i)} = U^{(i)} \Lambda^{(i)} V^{(i)H}$ , where  $U^{(i)}$  and  $V^{(i)}$  are unitary matrices,  $\Lambda^{(i)}$  is a non-negative diagonal matrix, the squares of diagonal elements of  $\Lambda^{(i)}$  are equal to eigenvalues of an  $\hat{H}^{(i)} \hat{H}^{(i)'} matrix, the columns of  $U^{(i)}$  are eigenvectors of the  $\hat{H}^{(i)} \hat{H}^{(i)'} matrix, and the columns of  $V^{(i)}$  are also eigenvectors of the  $\hat{H}^{(i)} \hat{H}^{(i)'} matrix; and$$$

$\Phi^{(i)}$  is a diagonal matrix having non-negative diagonal elements that determine channel power allocation and satisfy

$$\text{tr}(\hat{F}^{(i)} \hat{F}^{(i)'}) = \sum_{k=1}^{K_{ch,i}} \phi^{(i)}_{k,k}{}^2 = P_s, \text{ where } K_{ch,i} \text{ is a number of spatial channels}$$

to the ith receiver.

47. The method of claim 46, wherein the diagonal elements of  $\Phi^{(i)}$  are selected according to a criterion selected from the group consisting of:

15 a uniform power criterion,  $\phi^{(i)}_{k,k}{}^2 = P_s / K_{ch,i}$ ;

an MMSE (Maximum Mean Squared Error) criterion,

$$\phi^{(i)}_{k,k}{}^2 = 2\sigma_{\eta,i}^2 \left[ \frac{\mu}{\sqrt{\xi^{(i)}_{k,k}}} - \frac{1}{\xi^{(i)}_{k,k}} \right]^+;$$

an MSER (Minimum Symbol-Error-Rate) criterion,

$$\phi^{(i)}_{k,k}{}^2 = \frac{2\sigma_{\eta,i}^2}{\xi^{(i)}_{k,k}} \left[ \log \left( \frac{\xi^{(i)}_{k,k}}{2\sigma_{\eta,i}^2} \right) - \mu \right]^+; \text{ and}$$

an MCIR (Maximum Capacity and Information Rate) criterion,

$$\phi^{(i)}_{k,k}{}^2 = \left( \mu - \frac{2\sigma_{\eta,i}^2}{\xi^{(i)}_{k,k}} \right)^+,$$

where

$$(\bullet)^+ = \max(\bullet, 0) = \frac{1}{2}(|\bullet| + \bullet);$$

5  $\xi^{(i)}_{k,k} = \lambda^{(i)}_{k,k}{}^2$  are eigenvalues of the  $\hat{H}^{(i)}\hat{H}^{(i)'}$  matrix, and  $\lambda^{(i)}_{k,k}$  are diagonal elements of the  $\Lambda^{(i)}$  matrix; and

$\mu$  is a factor selected to define the MMSE, MSER, and MCIR criteria.

10 48. A computer program product comprising a computer-readable medium storing instructions which, when executed by a processor, perform the method of claim 39.

49. The method of claim 39, further comprising:

15 determining a plurality of demodulation matrices respectively corresponding to the sets of spatial coding weights;

transmitting the plurality of demodulation matrices from a transmitter to the receivers;

20 transmitting the weighted signals to the receivers over the plurality of communication channels; and

at each of the plurality of receivers:



receiving the weighted signals and the demodulation matrices;

determining the channel state information for a communication channel between the receiver and the transmitter; and

transmitting the channel state information to the transmitter.

50. A method comprising:

determining channel state information for a communication channel between a receiver and a transmitter;

transmitting the channel state information to the transmitter; and

receiving from the transmitter one of a plurality of demodulation matrices for demodulating subsequently received communication signals to which spatial coding weights comprising respective sets of spatial coding weights for a plurality of receivers have been applied.

51. A computer program product comprising a computer-readable medium storing instructions which, when executed by a processor, perform the method of claim 50.

52. A network element for processing signals to be concurrently transmitted to a plurality of communication terminals in a communication network, comprising:

an input configured to receive the signals; and

a processor configured to determine channel state information for each of a plurality of communication channels between the network element and the plurality of communication terminals, to determine a spatial coding matrix comprising a  
5 respective set of spatial coding weights for each of the plurality of communication terminals based on the channel state information, and to apply the spatial coding weights in the spatial coding matrix to the signals.

10 53. The network element of claim 52, wherein the input is further configured to receive portions of the channel state information from the plurality of communication terminals, and wherein the processor is further configured to combine the portions of the channel state information to thereby determine  
15 the channel state information.

54. The network element of claim 53, wherein the signals comprise respective groups of signals to be transmitted to the plurality of communication terminals, and wherein the processor  
20 implements a plurality of beamformers, each beamformer being configured to apply the sets of spatial coding weights to respective ones of the groups of the plurality of signals.

55. The network element of claim 52, implemented in a  
25 closed-loop multi-user MIMO (Multiple Input Multiple Output) communication system, wherein the processor of the network element is further configured to determine a respective demodulation matrix corresponding to each set of spatial coding weights, the network element further comprising:

a plurality of antennas for transmitting the respective demodulation matrices and the weighted signals to the plurality of communication terminals,

wherein the communication system further comprises a plurality of communication terminals, each of the plurality of communication terminals comprising:

a processor configured to determine the channel state information for communication channels of the plurality of communication channels between the communication terminal and the network element; and

at least one antenna for transmitting the channel state information from the communication terminal to the network element, receiving a demodulation matrix from the network element, and receiving the weighted signals from the network element,

wherein the processor of the communication terminal is further configured to demodulate the received weighted signals using the demodulation matrix.

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56. A communication terminal for operation in a communication network, comprising:

a processor configured to determine channel state information for communication channels between the communication terminal and a network element in the communication network; and

at least one antenna for transmitting the channel state information from the communication terminal to the network element, receiving a demodulation matrix from the

network element, and receiving signals concurrently transmitted to a plurality of communication terminals from the network element,

wherein the processor is further configured to  
5 demodulate the received signals using the demodulation matrix.